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A Taxonomy for Technology Models used in Environmental Impact Studies

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Abstract

This paper proposes classification of the technology models used in environmental analysis into three categories: detailed description of a thoroughly specified technology; general time dependent specification for technological domains; and most broadly with technology as a residual after accounting for other known drivers of change in environmental impact. The essence of each model is explained further in the paper with the fundamental differences among the three modeling approaches emphasized. This paper especially reviews the relative strengths and weaknesses of each of the three categories. Applications are noted for each category with combined applications of two approaches suggested as potentially offering the most value but such combinations have not yet received much attention.

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Keywords: sustainable technology; modeling technological change; Moore's Law; cost models; LCA models; IPAT

1. Background

The overall objective of this paper is to increase appreciation of the similarities and differences among existing approaches used to model technological change within engineering and policy work related to improving environmental outcomes. Since the engineering and policy efforts are quite generally associated with application of technology in various ways, the choice of a technological change modeling approach is a critical element in such work. Therefore, it is not surprising that a multitude of approaches have been utilized by various researchers and that each formulation of a problem brings with it consideration of different modeling issues. Although these considerations are predominantly within a given class of models, this paper stresses differences between classes of models. Indeed, the paper proposes to classify technological models for studying environmental impact into three classes. The first class is centered around the IPAT identity will be referred to herein as *environmental overview models*. The second class of models is focused upon the time dependence of environmental impact in given domains and will be referred to as *generalized Moore's law models.* The third class of models are the detailed models for products and processes often used in LCA (Life cycle assessment) for calculating cost, energy or environmental impact and will be referred to herein as *technological models for application in LCA*.

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Nomenclature

I	environmental impact (general term, usually per year, and applied to specific cases in the text)
P	global population
A	Affluence (usually -and in this paper- GDP per capita or GDP_c and is the global average)
T	symbolically represents "Technology" in most IPAT frameworks but also is the residual and arrived at by T = I/PA when these three terms are defined and quantified
Q	intensive technological performance (for example - energy stored per unit mass (watt-hrs/Kg) measured on an artifact developed at time t
k	Yearly relative improvement in Q
m_i	global material consumed annually in domain i
C	Cost
p	price
t	time
GDP	global economic output
ε_I	Income Elasticity (relative increase in consumption divided by relative increase in income)
ε_p	Price (or performance) elasticity- relative increase in consumption divided by the relative decrease in price, p, or the relative increase in performance, Q.
i	subscript i is used to denote a specific technological domain i
c	subscript c is used to denote per capita
y_m	yield in process step m
m	subscript m is used to denote process step m
n	subscript n is used to denote input n
Φ_{mn}	Amount of input n used in process step m

2. Environmental Overview Models (IPAT)

The broadest scale framework used for understanding environmental impact is known as the IPAT identity or IPAT equation. IPAT first emerged in the early 1970's as part of a fierce and extended debate about the relative importance of population and technology (broadly defined) in causing anthropogenic environmental impact. Ehrlich and Holden (1,2,3) held that population was the most serious problem to address whereas Commoner **strongly** (4,5) felt that technological change after WWII was a bigger cause for concern. The debate was emotional and never fully resolved; nonetheless, a framework evolved from the disagreement that has been widely useful in understanding the drivers of environmental harm. The framework is named for the four variables involved and is known as the IPAT identity:

$$I = PAT \tag{1}$$

Equation (1) states that environmental impact is the product of population times affluence times technology. Since affluence is generally proscribed as per capita GDP (GDP_c), the product of the first two terms is GDP. With specification of an environmental impact (for example Kg of CO_2 in year t), the technology or T term becomes the residual or the amount of the specified impact per unit of GDP (in this example, T would be kg of CO_2 in year t divided by $ of GDP with GDP also estimated for the year-or period- specified for I).

The IPAT identity has proven durable partly because of its simplicity/transparency and partly because of its flexibility in addressing a variety of environmental issues (sometimes specific pollutants and sometimes more general impact). There have been many useful extensions or elaborations of the identity and three will be mentioned here. The first example is the Kaya identity (6) which treats CO_2 emissions and factors the "T term" into the energy used per unit of GDP times the amount of CO_2 per unit of energy (all again in a specified time period). This factoring of technology helps one understand that low carbon energy sources like solar photovoltaics differ from energy efficiency technologies like improved energy efficient refrigerators. A more detailed decomposition (by industry sector, by fuel type, by material class, etc.) is a second example of IPAT elaboration and this particular type of analysis is now quite widely applied (7-12). The newly evolved field of industrial ecology has a "master equation" (13) that is directly based upon the IPAT identity and serves as a third example of extension. The master equation treats technology as a potential source of solutions and not only as a key driver or cause of environmental degradation as the original use denoted.

An excellent overview of these and other extensions and particularly of the history and importance of the IPAT identity is given in Chertow's essay (14). Regarding the core technology model in IPAT, it is covered similarly by Chertow and in the important papers by Dietz and Rosa (15, 16,17). Dietz and Rosa state on page 287 of their original paper (15)

> "*most social scientists are frustrated by the truncated visions of the rest of the world offered by the T in the IPAT model*"

And in footnote 28 they say:

> "*We have little social theory to suggest how to specify and measure T.*"

Similarly, Chertow (14) states

> "*Conceptually as well as numerically, P, population, and A, defined as a per capita measure of wealth, consumption, or production, have generally been more accessible to researchers than the T term.*"

Although the decomposition methodologies (6-12) successfully achieve greater clarity on important time trends that *depend on* some important aspects of technological change, these methods also do not specify a quantitative/predictive model for technological change. To our knowledge, there has not been noticeable progress in specifying technology in the IPAT framework since the publications by Dietz and Rosa (15) and Chertow (14) quoted above. Thus, the non-predictive nature of the technology term remains a major concern associated with the framework and existing extensions while a major advantage is its simplicity and transparency.